Pergamon

0094-5765(95)00024-0

*Acta Astronautica* Vol. 35, No. 9–11, pp. 753–761, 1995
Elsevier Science Ltd. Printed in Great Britain

# ACCESS-TO-SPACE: POTENTIAL FUTURE UNITED STATES LAUNCH VEHICLE TRANSPORTATION SYSTEMS†

UWE HUETER
NASA George C. Marshall Space Flight Center, Huntsville, AL 35812, U.S.A.

*(Received 1 July 1994; received for publication 6 February 1995)*

**Abstract**—The existing unmanned launch vehicle fleet of the United States consists primarily of Delta, Atlas and Titan. The Space Shuttle is currently the only United States manned launch vehicle. Future launch system needs, both unmanned and manned, have recently been studied by various "Blue Ribbon" committees, as well as by both the National Aeronautics and Space Administration and the Department of Defense. The main impetus for investigating new ways of providing access to space is the aging launch vehicle fleet and the large costs associated with providing that access. Many options have been and are currently being investigated to provide the United States with a road map for charting the future path for access to space. The advent of a permanent international facility in space, Space Station, will dictate that routine and economical access be provided.

This paper describes the systems being studied to improve the access to space by providing better, cheaper and more reliable launch systems capability. Architecture variations include both Space Shuttle improvements and phase-outs, new expendable launch vehicles, separate crew and cargo carriers and advanced technology crew and cargo vehicles.

## 1. INTRODUCTION‡

The existing unmanned launch vehicle fleet of the United States (U.S.) consists primarily of Delta, Atlas and Titan. The Space Shuttle is currently the only U.S. manned launch vehicle. The capability of the U.S. to be able to support its domestic space transportation needs has been steadily eroding due to fleet aging, subsystem and component obsolescence and international competition. Future launch system needs, both unmanned and manned, have recently been studied by various "Blue Ribbon" committees, as well as by both the National Aeronautics and Space Administration (NASA) and the Department of Defense (DoD). The main impetus for investigating new ways of providing access to space is the aging U.S. launch vehicle fleet and the large costs associated with providing that access. Secondary factors include improvements in vehicle reliability, full mission abort modes for manned vehicles, advances in technologies and environmentally cleaner propellants.

The separation of crew and cargo for Space Shuttle missions may result in savings in launch cost for the missions not requiring man's presence. Many options have been and are currently being investigated to provide the U.S. with a road map for charting its future path for access to space. The advent of a permanent international facility in space, Space Station (SS), will dictate that routine and economical access be provided. The operation of the Space Shuttle currently requires approximately one-third of the total NASA budget. This, plus the cost of developing SS results in minimal available funding for future programs. Therefore, unless NASA experiences major budget growths in the future, the development of any new launch vehicle capability will require that initial investment cost be minimized. For the past several years the U.S. budget has been increasingly constrained in the amount of funding available to support the Government's launch services needs, with NASA and DoD likely to see relatively flat budgets, when adjusted for inflation, for the foreseeable future.

The next generation of U.S. launch vehicles must dramatically lower the cost of space access. Current costs are such that many potential space missions and experiments are excluded simply due to launch costs. Only the nation's highest priority activities are launching today. The cost of space access is consuming so many resources (budget, talent and facilities) that we have too little remaining to undertake the bold, aggressive and exploratory endeavors that push our technology, imaginations and spirits.

The purpose of the Access-To-Space (ATS) study was to define a strategy to meet future space transportation needs focusing primarily on improved reliability and crew safety and significant reduction in

†Paper IAF-93-V.3.621 presented at the *44th International Astronautical Federation Congress*, Graz, Austria, 16–22 October 1993.

‡See Nomenclature at the end of this paper.

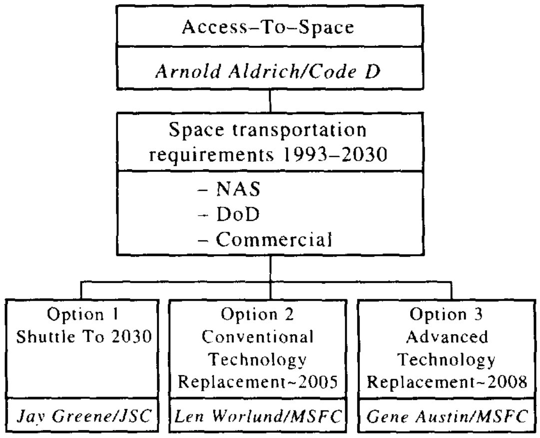



Fig. 1. Study team organization.

annual operations costs. This paper summarizes the ATS study and presents its results.

## 2. OBJECTIVE

During the period of August through November of 1992 a number of internal NASA reviews were conducted as a precursor to assessing access to space requirements. In January of 1993, NASA Administrator Daniel Goldin announced the establishment of a detailed study to define potential improved access to space implementation strategies. The main objectives were to improve crew safety and vehicle reliability and significantly reducing the operating cost. The ATS study team was formed and its steering group identified three major space transportation architecture options, resulting in teams to support each option. The team organization is shown in Fig. 1.

The focus of the Option 1 team was to identify improvements needed to maintain the Space Shuttle fleet through calendar year (CY) 2030. The Option 2 team was to identify requirements for replacing the Shuttle fleet by CY 2005 with a new fleet of expendable launch vehicles (ELVs) that utilized conventional technologies. The Option 3 team focus was to identify requirements for replacing the Shuttle fleet by CY 2008 with a new fleet of fully reusable launch vehicles that utilized advanced technologies.

| Vehicle Class | NASA | Commercial | DoD |
|---|---|---|---|
| Pegasus/ Taurus Class | 2 | 1 (Nominal)<br>8 (Growth) | 2 |
| Delta Class | 3 | 1 (Nominal)<br>3 (Growth) | 6 |
| Atlas Class | 2 | 3 (Nominal)<br>3 (Growth) | 3 |
| Titan Class | 0.3 | 0 | 3 |
| Shuttle Class | 8 | 0 | 0 |

Fig. 2. Average annual launch demand (1995 → 2030).

## 3. REQUIREMENTS

The requirements used for this study were based on the NASA Civil Needs Database (CNDB) and the U.S. Air Force Space Command Mission needs Statement. Based on the 1990 modified CNDB, approximately 90% of all future low Earth orbit (LEO) payloads were those whose injected masses were under 9.1 t and whose lengths were under 6.1 m. Each year there were approximately 23 payloads, other than those supporting SS, in the 4.5–9.1 t class. The 9.1 t LEO payload class were equivalent to injecting a 2.3 t payload into geosynchronous orbit (GEO). Based on the mission model, the average annual launch demand used for this study is shown in Fig. 2.

The primary vehicle driver for post-2000 access to space was the SS logistic. Based on current requirements for SS permanently crewed capability, the total annual mass to orbit, including logistic carriers, was 92.7 t, with a return requirement of 82.3 t. The net annual logistics required, excluding carriers, was 68.2 t delivered to SS and 57.7 t returned to Earth. The primary SS logistic carriers were pressurized modules and unpressurized carriers. Support for satellite servicing missions at a rate of approximately once every 3 years was also required.

## 4. EVALUATION CRITERIA

The ATS steering group provided a set of evaluation criteria, see Fig. 3, to be used by all options. The fundamental requirement was to satisfy all national launch needs. The essential characteristics were improved safety, reduced cost and environmentally acceptable vehicles. Other desirable features, such as commercial competitiveness and improved capability, were also specified.

| Fundamental Requirement | Essential Characteristics | Desired Features |
|---|---|---|
| • Satisfy The National Launch Needs<br>• Commercial<br>• National Security<br>• Civil Space unmanned<br>• Civil Space manned<br><br>Includes definition of payloads from small to exploration class, and destinations at all inclinations | • Improves crew safety (survivability ≥ 0.999)<br>• Acceptable life cycle cost to include:<br>• Affordable DDT & E<br>• Improved operability & annual operating cost reduction over current systems (for STS equivalent ≤ 50%)<br>• Acceptable program risks (technical, cost, schedule)<br>• Vehicle reliability of at least 0.98<br>• Environmentally acceptable – meet all requirements planned for year 2002 | • Improves commercial competitiveness of launch vehicles<br>• Contributes to industrial economy (dual-use technology and processes)<br>• Enable incremental development or improvements<br>• Improve capability relative to current systems (including STS) |

Fig. 3. Evaluation criteria.

## 5. OPTION 1—SHUTTLE TO 2030[1]

### 5.1. Approach

The Option 1 objective was to use Space Shuttle heritage, hardware elements and operations experience to develop a more economical system by reducing operational and hardware costs through design changes. The Option 1 team approach was to establish which hardware changes could be economically implemented as opposed to replacement of the system. New management approaches and changes in philosophy were not addressed as part of this study.

An evolutionary design approach was chosen for the Shuttle since the existing system is the world's only transportation system that has demonstrated the capability of launching, retrieving and returning payloads to and from space. It has demonstrated a high success rate, on-time launch performance comparable to expendable systems, and the cost per pound of payload within range of other existing systems. It is anticipated that a 25% cost reduction is possible for the Shuttle system by 1996, with further reductions expected by 2000. The study considered three evolutionary options (see Fig. 4): Retrofit, New Build and New Mold Line.

### 5.2. Findings

Over 200 candidate changes to mitigate or eliminate 90 cost drivers were identified. Development cost and operations cost savings were the major criteria used for selecting candidate changes for incorporation into the Retrofit and New Build evolution options. Technology identification and programmatic new starts were assumed to occur in 1998.

Several areas of potential improvement were identified that could take advantage of modern technology. Among these were the thermal protection system (TPS), which could see improvements through use of advanced materials such as advanced flexible organic and ceramic blankets, advanced carbon–carbon (ACC) and new tougher tile coatings and development of non-destructive evaluation techniques to assess TPS life. Improvements to the orbital maneuvering system (OMS) and the reaction control system (RCS) included propellant valves changes and alternate non-hypergolic propellants, e.g. liquid oxygen and ethanol. The considered avionics changes included modernizing and integrating the avionics subsystems. New computers, improved displays, fiberoptics, use of the global positioning system and vehicle health management (VHM) were some of the changes assessed. Electrical and power system upgrades included long life and high power density fuel cells, electrical auxiliary power units and electro-mechanical actuators (EMAs). Structural candidates included use of aluminum–lithium, improved corrosion resistance for the rudder speed brake and improved access for inspection. Environmental control and life support system improvements included replacing Freon 21, using a cryogenic boiler or thermal wax pack rather than the ammonia boiler and replacing the current waste collection system. Other system assessments included improved leak tight joints in the main propulsion system, more reliable valve position indicators, use of composites and use of heat sinks as an alternative TPS for the external tank. Also considered were EMAs and laser initiated pyrotechnics for the Solid Rocket Booster. Other major changes studied were crew escape systems, use of ejection seats or an escape pod and reusable flyback liquid rocket boosters to replace the current solid boosters.

| Retrofit | New build | New mold line |
|---|---|---|
| • Vision 2000 improvements assumed accomplished | • Retrofit improvements assumed to be accomplished | • New build improvements assumed accomplished |
| • Additional modifications during an extended modification period | • New orbiter build | • New orbiter build |
| • No changes to orbiter outer mold line | • No changes to orbiter outer mold line | • Major external changes to orbiter outer mold line |
| | | • Major internal modifications to orbiter |

Fig. 4. Shuttle evolution options.

### 5.3. Summary

A list of near-term Shuttle improvements, an evolution plan for all Shuttle subsystems and an advanced development/technology plan were developed. The team found no compelling reasons to alter the outer mold line of the Orbiter. Additional crew escape capability was not recommended because of the associated performance and cost penalties. However, the team felt that an unmanned Orbiter could remove current payload restrictions and that cost per flight could be reduced by the potential subsequent increased flight rate. Development of a reusable flyback booster was the only alternative booster candidate that had economic potential to compete with the current solid rocket boosters.

It was concluded that the current four Orbiter fleet would need to be augmented to continue flying for the long term. Areas requiring further study were payload accommodations, flyback boosters, VHM and alternative management approaches.

## 6. OPTION 2—CONVENTIONAL TECHNOLOGIES[2]

### 6.1. Approach

The Option 2 objective was to satisfying the nation's space transportation needs with conventional technology. The basic premise was to phase out the existing U.S. launch vehicles and replace them with new vehicles using technology available in 1997. The Space Shuttle was to be phased out by 2005.

To meet the Shuttle requirements, approximately 20 concepts of both crew and cargo vehicles were assessed. The concepts were divided into a development of a single airframe for both crew and cargo vehicle or separate crew and cargo vehicle developments. To improve crew safety, smaller vehicles were thought to provide better abort capability. Also, the separation of crew and cargo reduced the exposure of the crew. To reduce operational cost and improve reliability, precision (runway) landers were preferred over parachute landing concepts.

The smaller vehicles required increased flight rates due to the large required return mass and their small cargo carrying capacity. This increased the operational costs to unacceptable levels. Therefore, to improve the operational costs, both full logistics and minimum logistics return scenarios were assessed. The current SS baseline was to return 82.3 t (including logistics carriers). If the carrier weights were removed, the total baseline requirement became 57.7 t. Analysis conducted by Langley Research Center (LaRC) showed that the baseline return could be lowered from 57.7 to 29.5 t by selecting to return only the spares, user and crew systems hardware that were planned for reuse or scientific data return (i.e. do not return trash that will be disposed). To further reduce the return logistics, the returned items were examined and the following rationale developed:

- Only high value scientific items returned
- No experiment returned (only samples)
- No spares or maintenance items returned
- No unpressurized structure returned
- No carriers returned
- No subcarriers returned

The priority items to be returned were as follows:

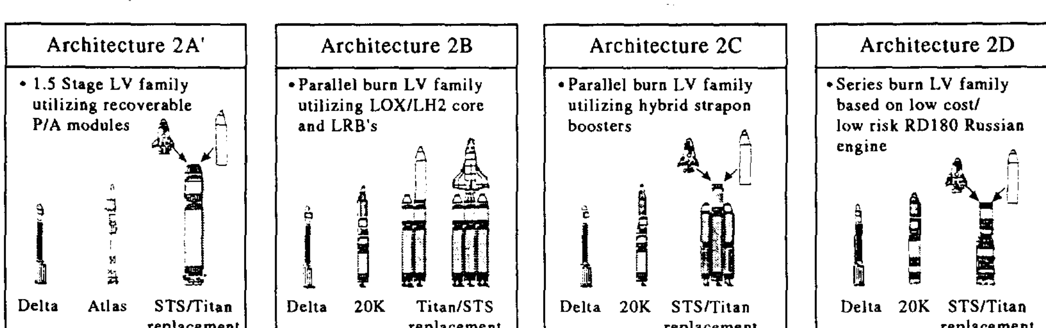
- Late/early access mid deck lockers
- Essential experiments
- EVA suits

The result was that approximately 10 t of logistics would need to be returned. Based on the preceding rationale, two primary crew and/or cargo vehicles, HL-42 (for minimum logistic return) and CLV-P (for full logistic return), were selected.

The launch vehicle selection began with approximately 100 candidates, which were rapidly screened to 28 based upon propellant choice and performance. These were subjected to closer scrutiny considering cost, safety, risk and other factors. The selection of the crew and cargo vehicles and the matching with preferred launch vehicles, resulted in four selected architectures (2A′, 2B, 2C and 2D).

### 6.2. *Architectures*

The four selected architectures, depicted in Fig. 5, were referred to as 2A′, 2B, 2C and 2D. Each satisfied the basic requirements of payloads to LEO and GEO. Common across all four was the use of an upgraded Delta vehicle for 4.5 t payloads, and a single engine Centaur high energy upper stage. Architectures 2A′, C and D assumed that the SS reduced logistics return approach was acceptable. Architecture 2B provided full logistics return capability.




Features:

- Delta for 10K Class
- Atlas for 20K Class
- STS/Titan replacement Class
  - -- HL-42 for crew trans.
  - -- ATV for cargo trans.
  - -- Single eng. Centaur
  - -- 1.5 Stage parallel burn
  - -- All LOX/LH2
  - -- Part. reusable (P/A)
  - -- SSME

Features:

- Delta for 10K Class
- New 20K to replace Atlas
- STS/Titan replacement Class
  - -- Full station logistics return
  - -- CLV-P for crew & cargo
  - -- Single eng. Centaur
  - -- 2 Stage parallel burn
  - -- All LOX/LH2
  - -- Expendable LV elements
  - -- Low cost, STME
  - -- Commonality: boosters/core/20K

Features:

- Delta for 10K Class
- New 20K to replace Atlas
- STS/Titan replacement Class
  - -- HL-42 for crew trans.
  - -- ATV for cargo trans.
  - -- Single eng. Centaur
  - -- 2 Stage parallel burn
  - -- LOX/LH2 core
  - -- Hybrid booster
  - -- Expendable LV elements
  - -- Low cost, STME
  - -- Commonality: core w/20K

Features:

- Delta for 10K Class
- New 20K to replace Atlas
- STS/Titan replacement Class
  - -- HL-42 for crew trans.
  - -- ATV for cargo trans.
  - -- Single eng. Centaur
  - -- 2 Stage series burn
  - -- LOX/RP booster
  - -- LOX/LH2 2nd stage
  - -- Expendable LV elements
  - -- RD180/J2S

*(Note: 10K and 20K refers to approximate vehicle capability to LEO in 1,000's of pounds)*

Fig. 5. Option 2 architecture overview.

Architecture 2A′ represented a minimum initial investment and recurring hardware cost scenario through the use of existing propulsion systems and by recovering the vehicle's propulsion and avionics hardware. An upgraded Atlas vehicle was used for 8.1 t payloads. Unmanned 29.5 t requirements were satisfied with a Titan replacement in 2002. After the Shuttle phaseout in 2005, the same launch vehicle was used for ELV payloads, HL-42 for SS crew rotation and ATV for SS logistics support. The launch vehicle consisted of 1.5 stages, using three two-engine recoverable propulsion/avionics modules. Two modules acted as boosters and were staged during the ascent flight. The engine used was the Space Shuttle Main Engine (SSME).

Architecture 2B represented a launch vehicle family that was built on a common diameter core and booster. A new 9 t class vehicle with low cost, advanced technology gas generator cycle engine, Space Transportation Main Engine (STME), was proposed. This vehicle was used as the core stage on the Titan replacement vehicle, which also used a single two engine strap-on liquid booster. For crew and logistics support to the SS, the CLV-P was used with the launch vehicle having two liquid boosters. The advantage of this architecture was that full SS logistics return requirements were met.

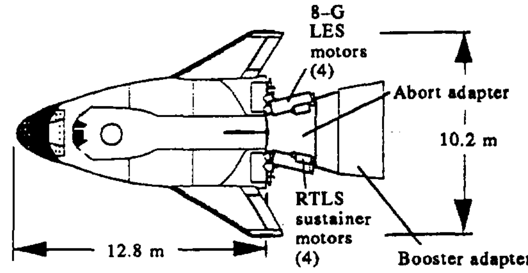
Architecture 2C provided an architecture that utilized hybrid boosters to reduce the cost of the liquid boosters used in Architecture 2B. The same 9 t class vehicle as in Architecture 2B, with a slightly lower engine thrust level, was used. The Titan/Shuttle replacement vehicle used the liquid core with two hybrid boosters. For SS support, the HL-42 (crew rotation) and the ATV (logistics support) were required.

Architecture 2D represents a serial burn two-stage vehicle configuration that utilized both U.S. and foreign existing assets to reduce initial investment costs and shorten the development schedule. The 9 t class vehicle used a single RD-180 engine (a Russian engine derived from the existing RD-170 with half the thrust). The Titan/Shuttle replacement used a new first stage with three RD-180 engines, a second stage with a J-2S engine and the HL-42 and ATV for SS support.

### 6.3. *HL-42*

The HL-42 design was derived directly from the lifting body concepts that have been under study at the LaRC since 1983. The vehicle was a horizontal lander that retained the key design and operational features of the lifting body database, which included aerodynamic, abort, flight simulation and human factors information.

The vehicle was a fully reusable spacecraft designed to be placed into LEO by an expendable booster. Figure 6, illustrates the HL-42 concept. Launch escape motors used for emergency abort were attached to the expendable vehicle adapter at the base of the spacecraft. The basic structure was a cylindrical aluminum–lithium cabin with a graphite–polyimide heat shield. The TPS consisted of tailored advanced blanket insulation (TABI) and flexible reusable surface insulation (FRSI) blankets which were bonded directly to the structure. Leading edges, such as fins and nose cap, use ACC. There were seven moving surfaces for flight control, including four body flaps, two elevons and a movable vertical tail. Control was effected by EMAs. Power was provided by fuel cells with silver–zinc batteries used for peak power loads. The vehicle did not have a main propulsion system, but used methane/liquid oxygen OMS and RCS. The OMS system provided a $\delta v$ capability of 290 m/s, which was sufficient for transfer, circularization, rendezvous to a 407 km orbit and de-orbit. Re-entry was limited to 1.5 $g$. The vehicle had a cross range capability in excess of 1852 km for expanded landing opportunities. During ascent and descent, the vehicle operated in an autonomous mode not requiring a pilot.



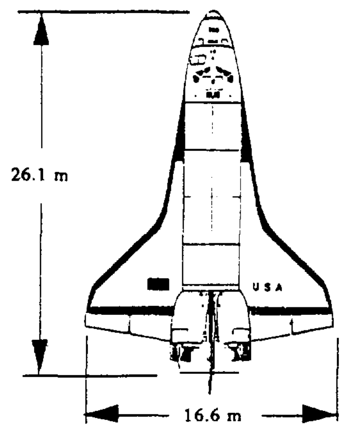

| | |
|---|---|
| Dry weight | 13.40 t |
| Launch weight | 28.80 t |
| On-Orbit weight | 21.14 t |
| Payload capability | 4.23 t |

Fig. 6. HL-42 design.

### 6.4. *Crew Logistics Vehicle (CLV-P)*

The CLV-P was essentially a scaled Space Shuttle Orbiter (70% in length and 75% in cross-section), sized to satisfy Station requirements while using updated technology where appropriate, see Fig. 7.

The basic vehicle structure was aluminum, with the rudder, speed brake and body flaps constructed of ACC. The TPS used TABI, tiles similar to the current Orbiter and ACC for leading edges. EMAs were used for aero-surface control, landing gear actuation, braking and nose wheel steering. Power was provided through use of long life fuel cells for base power and high power density fuel cells for EMA actuation. An updated avionics suite used an integrated management unit with an inertial navigation system, global positioning system for tracking, radar altimeter and an air data system. The vehicle did not have a main propulsion system. The OMS and RCS used ethanol and liquid oxygen. The OMS $\delta v$ of about 258 m/s



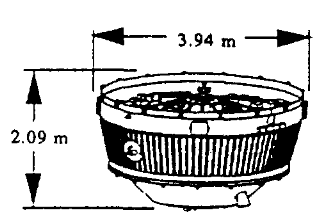

| Pressurized configuration | |
|---|---|
| Dry weight | 31.40 t |
| Gross weight | 47.45 t |
| Launch weight | 48.23 t |
| Payload capability | 7.73 t |

Fig. 7. CLV-P design.

provided SS orbit capability. The minimum cross range capability upon entry exceeded 1852 km to enable the vehicle to land at Edwards Air Force Base or White Sands in case of weather problems at KSC. During ascent and descent, the vehicle operated in an autonomous mode not requiring a pilot. A crew ejection system was provide in event of an abort.

*6.5. Cargo Transfer Vehicle (CTV)*

A transfer vehicle was required to provide unmanned logistics resupply to the Station and to destructively re-enter with expendable SS logistics. It also provided the capability to deliver replacement modules to the Station. A transfer vehicle was required in architectures 2A′, 2C and 2D as the prime method of SS logistics delivery and module placement. In architecture 2B, the transfer vehicle was required only if a module required replacement.




| | |
|---|---|
| Dry weight | 1.90 t |
| Gross weight | 5.65 t |
| Payload capability | 16.00 t |

Fig. 8. ATV design.

Eleven existing and conceptual transfer vehicles were considered in this study, including: the U.S. CTV from the National Launch System baseline design; Lockheed Bus 1; the European Automated Transfer Vehicle (ATV); and the Russian Salyut Space Tug. The Salyut Tug was eliminated early since little cost information was available.

The U.S. CTV and European ATV were found to be essentially equal in performance and flight costs. However, the ATV, shown in Fig. 8, was judged to be the most cost effective solution since it minimized U.S. development costs.

*6.6. Operations*

Ground rules and guidelines consistent with an operationally efficient launch system and attendant reduced costs were established. Several areas were eliminated from design consideration to minimize costs, including:

- Solid rocket motors as core and booster stages
- Hydraulics
- Hypergolic propellants

Increased capability was added to other areas, including:

- An integrated health management system for ground test and checkout
- Vehicle and payload elements delivered to the launch site in flight ready condition
- Elimination of test and checkout procedures already accomplished at the manufacturing facility.

Other significant programmatic philosophy changes included flight handover to mission control at payload separation instead of tower clearance, and automated launch, ascent, mission operations, re-entry and landing.

*6.7. Schedules and cost*

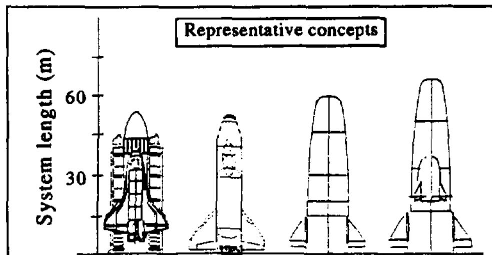
Meeting the schedules of Titan replacement in 2002 and Shuttle phaseout by 2005 was shown to be feasible. The earliest required start was mid-1996 for the development of the new engines. Most other activities must be started by 1997 or 1998. The development of the propulsion system was the main schedule driver.

DDT&E, production, and operations costs were estimated over the life of the program. Life cycle costs for architectures 2B, 2C and 2D were roughly comparable, with architecture 2A′ the least expensive. Peak funding for all architectures occurred around 2000. The funding peak was 2–2.5 times that required during the post-2005 operational phase.

*6.8. Summary*

All the architectures identified satisfied the national space transportation needs. Architecture 2A′ was the least expensive for long Titan/Shuttle class payloads, while architecture 2D was the lowest cost for the

9 t class vehicle. Crew safety was improved by safer aborts for all mission phases, the elimination of solid rocket boosters and less crew exposure since the manned flights were reduced through the use of expendable cargo vehicles. Environmental concerns were somewhat alleviated by not using solid rockets and hypergolic propellants. Significant cost reductions, increased reliability and increased crew safety can be accomplished relative to current systems. The architectures identified offered distinct advantages in performance, reliability, operability, autonomous flight control and growth capability for next generation systems. Based on the criteria established for the study, architecture 2D was the preferred approach by the Option 2 team.




| Vehicle | Shuttle | Single stage vehicle | Single stage vehicle | Two stage vehicle |
|---|---|---|---|---|
| Propulsion | Rocket | Rocket | Airbreather/ rocket | Airbreather/ rocket |
| GLOW | 2043 t | 1135 t | 416 t | 364 t |
| Dry weight | 230 t | 106 t | 108 t | 138 t |
| Payload to 185 km circ @ 28.5° | 24.4 t | 20.4 t | 23.6 t | 14.5 t |

*New systems deliver 11.4 t to SSF @ 51.6° inc. (unmanned)*

Fig. 9. Option 3 vehicle concepts.

## 7. OPTION 3—ADVANCED TECHNOLOGY [3]

### *7.1. Approach*

To substantially reduce the cost of access to space, Option 3 focused not only on the vehicle concepts, but also, on improving every aspect of the program. Major emphasis was placed on significantly reducing the operational costs. Based on this philosophy, the vehicle design must reduce the number of elements, technology must focus on improving operations, program changes must be kept to a minimum, sustaining engineering must be reduced significantly during the operations phase and the flight design must have adequate performance margins to eliminate tailoring the mission profile for each flight.

Considering all the payload requirements, the advanced technology vehicle concepts were based on a payload capability of 11.4 t to a 407 km circular orbit at an inclination of 51.6°. The payload bay was established to be 4.6 m in diameter and 9.1 m long. To meet the payload requirement of 18–23 t to LEO, an ELV of the Titan IV class was used. Alternate concepts utilizing larger payload bays and increased payload capability, to eliminate the ELV requirement, are currently being studied.

### *7.2. Transportation options*

Three launch vehicle concept design options (see Fig. 9) were chosen by the Option 3 team for engineering analysis and costing, as representative of the numerous fully-reusable vehicle concept possibilities. In terms of technology requirements for reusable launch systems, these three concepts were identified because they represented the largest range of candidate vehicle options. It should be noted that these concepts only served as "representative vehicles" for technology and operations evaluations. No final concept recommendations were made.

The design philosophy of the single stage to orbit (SSTO) rocket vehicle was to maximize the lessons learned from the Space Shuttle program and apply the minimum technology required to allow for an operationally efficient vehicle. To improve the performance margins, the use of advanced technologies are currently being studied. The SSTO rocket reference vehicle was a vertical-takeoff, horizontal-landing winged concept with a circular-cross-section fuselage for structural efficiency. The payload bay was located between an aft liquid hydrogen tank and a forward liquid oxygen tank. The propellants were contained in integral, reusable cryogenic tanks. The vehicle employed wing tip fin controllers for directional control. The crew was accommodated in the crew module located in the cargo bay. Crew control was only required during on orbit operations for satellite servicing missions. The vehicle employed a standardized payload canister concept with common interfaces that allowed off-line processing of payloads and rapid payload integration. All non-pressurized primary structural materials were graphite-composite drawing on current airplane and rocket designs. The TPS was composed of ACC for the control surfaces, nose cap and wing leading edge. The remaining areas of the wing and body were covered with advanced flexible surface insulation (AFRSI) where ascent /entry stagnation temperatures stayed below 650°C, or TABI where stagnation temperatures remained below 1100°C. The main propulsion system for the SSTO rocket concept consisted of seven evolved SSMEs, a pressurization and feed system, engine gimbals and engine-mounted heat shields. The lift-off thrust-to-weight ratio was 1.2. Other options, such as the use of tripropellant engines (e.g. the Russian RD-701 engine or equivalent) are extremely attractive and currently considered a strong contender for this concept.

The airbreathing/rocket powered SSTO concept was a horizontal takeoff and landing vehicle. The propulsion system was derived from the National Aerospace Plane concept. Takeoff and transonic ascent were accomplished with a low-speed airbreathing system (ramjets and scramjets) and the rocket performing simultaneously. The rocket was shut down at approximately Mach 1.8. The ramjet mode was initiated at Mach 3. Transition to the scramjet started at Mach 6 with full scramjet operation by Mach 7.5. Departure from the isobar above Mach 15 signalled the onset of liquid oxygen augmentation through the scramjet and the activation of the external rocket system. Scramjet main engine cutoff was at Mach 24.

The two stage to orbit (TSTO) concept utilized low level technology to reduce risk, yet was sufficiently advanced so that the performance and operations cost were comparable to the single stage systems. Staging can give either increased performance for a given technology level or equal performance with less advanced technology and lower risk. The TSTO was not a new concept and there have been several design studies that show multiple solutions and a mature design base for the concept. The booster used conventional turbofan jet engines and subsonic burning ramjets. A turbofan was used for flight to Mach 2.4 and was based on a cycle used in studies for a next-generation supersonic transport. Similar cycles were used in older military engines such as the J-58 used in the SR-71, that fly at higher speeds. At Mach 1.05, the turbofan was augmented by a subsonic burning ramjet, which also provided all of the thrust from Mach 2.4 up to the staging speed of Mach 5. Both of these engines can be qualified in existing ground test facilities. The cycles have been previously demonstrated in aircraft or in ground tests. The second stage used an expander cycle rocket engine. The expander cycle provided a well proven design with greater simplicity and reliability than other engine cycles, such as the gas generator and staged combustion cycles, but at a decreased performance efficiency. The booster used a shape derived from past programs and technology developed in the NASP program.

### 7.3. Technology

After reviewing each configuration, it was evident that the following core technology areas were essential for the development of all three concepts:

- Reusable cryogenic tanks
- Low-maintenance TPS
- Autonomous flight control
- Operations enhancement technologies
- Vehicle health management
- Light weight structures

It is possible to develop these enabling technologies without having to select a given configuration or concept. In addition to the above listed core technologies, several enabling technologies were unique for each concept. As previously mentioned, a tripropellant engine (RD-701 or equivalent) development for the SSTO rocket concept would greatly enhance its performance margins. An extensive program in airbreathing propulsion, actively cooled TPS, slush hydrogen production and transfer and advanced material development was required for the airbreathing/rocket SSTO concept. The TSTO concept required technology development for both airbreathing and rocket propulsion systems and advanced materials (e.g. titanium matrix composites).

### 7.4. Operations

All modern aerospace endeavors incorporated the following three fundamental program approaches:

- Design in modern technology that can deliver a simpler vehicle
- Halt flight-by-flight vehicle certification
- Manage for operations

This approach will lead to a launch capability with fewer facilities, fewer people, fewer unique tools and much lower costs. Analyses of ground processing and flight operations have shown a substantial reduction in the complexity of operations facilities and personnel required to conduct space launches for each vehicle option. Well-established flight margins, along with a VHM system will reduce both preflight and postflight testing operations. Additionally, since these vehicles would be fully reusable, significant cost savings were realized by the elimination of continuing production. The costs of mission design and operations were substantially reduced by the incorporation of modern operations technology and philosophies. A mission manager, along with a small team of engineers, would be assigned to each vehicle and given responsibility for mission design, definition of unique mission software and real-time mission support.

### 7.5. Summary

The Option 3 team determined that the SSTO vehicle was a feasible system that can achieve the ATS objectives and provide major life cycle cost and performance benefits. Technology options exist that can be matured in this decade that, for the first time, make an SSTO vehicle feasible. Figure 10 illustrates the historical trend of vehicle mass fraction as a function of engine performance and available material. As shown, it now appears that advances in

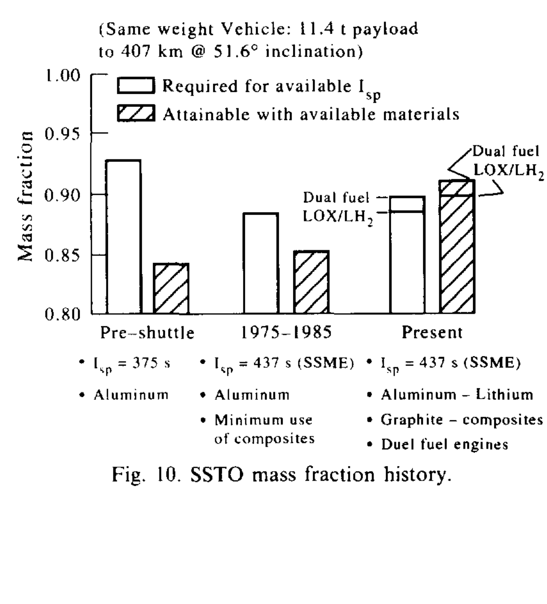



Fig. 10. SSTO mass fraction history.

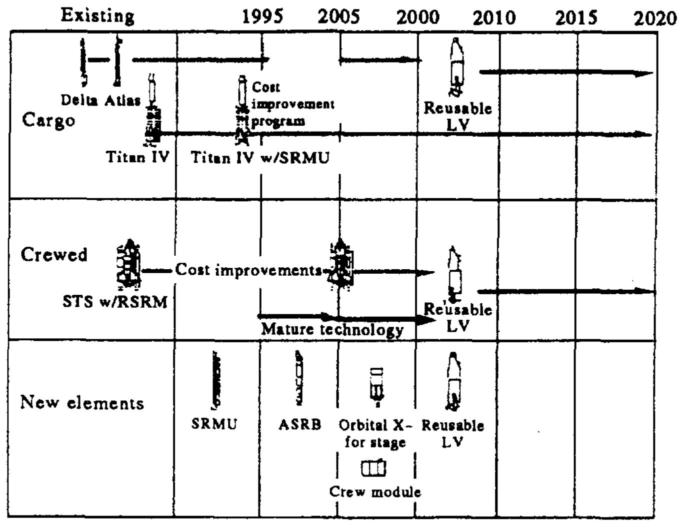



Fig. 11. Option 3 recommended architecture.

both engine performance and material technology have made the SSTO rocket concept feasible.

Figure 11 shows the recommended Option 3 architecture. Cargo and crewed missions are shown along with requirements for major new elements and the approximate time frame of their implementation. The reusable launch vehicle icon shown in the figure represents any one of the three candidate reusable launch system concepts. The position of the Option 3 team was that a concept downselect is not currently needed, since the majority of the enabling technologies were found to be common for the three vehicle concepts.

## 8. CONCLUSION

To accomplish the significant reductions in access to space cost, every aspect of the program will require a substantial paradigm shift from current experience. Technology investment must focus on improved operations. Vehicle designs must reduce the number of dissimilar elements. Program changes during the operations phase must not be allowed, except for work changes. The design must possess proper flight performance margins, obtained through an extensive ground and flight test program, to allow standardization of ascent, on-orbit and entry flight profiles.

The study has shown that operations cost reductions can be achieved for all three options. Option 3, the fully reusable concepts, showed the greatest potential for recurring cost savings. However, substantial initial investments both in technology/advanced development and vehicle development will be required.

The White House, in conjunction with NASA, DoD and other pertinent agencies, is currently studying what the future U.S. national launch policy should be.

## REFERENCES

1. Access-to-space—Option 1. Final presentation to Arnold Aldrich, August (1993).
2. Access-to-space—Option 2. Final Report, September (1993).
3. Access-to-space—Advanced Technology Team. Final Report, July (1993).

## APPENDIX

*Nomenclature*

ACC = advanced carbon–carbon
AFRSI = advanced flexible reusable surface insulation
ATS = access-to-space
ATV = automated transfer vehicle
CLV = crew logistics vehicle
CNDB = civil needs database
CTRV = cargo transfer and return vehicle
CTV = cargo transfer vehicle
CY = calendar year
DDT&E = design, development, test and engineering
DoD = Department of Defense
ELV = expendable launch vehicles
EMA = electro-mechanical actuators
FRSI = flexible reusable surface insulation
GEO = geosynchronous orbit
JSC = Johnson Space Center
LaRC = Langley Research Center
LEO = low Earth orbit
LES = launch escape system
MSFC = Marshall Space Flight Center
NASA = National Aeronautics and Space Administration
OMS = orbital maneuvering system
PLS = personnel launch system
RCS = reaction control system
SS = Space Station
SSME = Space Shuttle main engine
SSTO = single stage to orbit
STME = space transportation main engine
TABI = tailored advanced blanket insulation
TPS = thermal protection system
TSTO = two stage to orbit
U.S. = United States
VHM = vehicle health management